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ABSTRACT

Two-stroke cycle engines used for modern snowmobiles produce high-levels of carbon monoxide and unburned hydrocarbons. In order to address the emissions and noise issues resulting from the use of snowmobiles, the Clean Snowmobile Challenge 2000 was held under the auspices of the Society of Automotive Engineers. The CSC 2000 competition was intended to facilitate the development of high-risk concepts to address the negative impact of snowmobiles. Hydrocarbon emissions from two-stroke cycle snowmobile engines are primarily due to short-circuiting of the air/fuel mixture during the scavenging process. Carbon monoxide emissions are due to rich combustion mixtures and poor combustion produced by inefficient scavenging. A student research team at Colorado State University undertook an ambitious engine development project for the competition. An externally-scavenged, direct-injected engine was designed to reduce emissions, improve fuel economy, maintain or improve power, and reduce exhaust noise. A twin-screw compressor was used to provide external scavenging for the engine. The Ficht™ impact-type fuel injection system was used to provide direct in-cylinder fuel injection. A high efficiency multistage reaction / absorption silencer was designed which also houses an oxidation catalyst. The engine was developed to the point that it is operational, although it was not used in the CSC 2000 competition. This paper describes the design concept for CSU's new snowmobile engine.

INTRODUCTION

Growing concerns about ambient air quality have profound implications for the engines used in the recreational vehicles. This is particularly true for the snowmobile industry, as demonstrated by a recent ban on snowmobile operation in most national parks. Almost all production snowmobiles utilize simple crankcase-scavenged two-stroke cycle engines. These engines are simple, robust, and lightweight; they have an exceptional power-to-weight ratio. Unfortunately, the two-stroke technology used for today's snowmobiles produces high levels of hydrocarbon and carbon monoxide emissions. These engines can also produce objectionable levels of engine exhaust noise.

A student research team at Colorado State University undertook the task of developing a new powerplant for use in the SAE Clean Snowmobile Challenge (CSC 2000) competition. The objectives were to reduce emissions and noise while maintaining or improving vehicle performance and fuel economy.

POWERPLANT SELECTION

Both two-stroke and four-stroke cycle engines were considered for this application. Four-stroke cycle engines avoid one of the major problems inherent in two-stroke cycle engines – fuel loss during scavenging which causes high hydrocarbon emissions. Four-stroke cycle engines, combined with exhaust catalysts, show very clean emissions in automobiles and moderately clean emissions when used without catalysts in motorcycles and all-terrain vehicles. Unfortunately, snowmobiles require continuous power levels which are difficult to achieve, using four-stroke engines, without incurring severe weight penalties. In addition, the cams and valves on the four-stroke cycle engine add complexity and can reduce reliability.

The psychology of rider satisfaction played a major role in the final "2-stroke vs. 4-stroke" decision. The four-stroke cycle snowmobiles demonstrated to date show disappointing performance due to low power levels. If snowmobile buyers are presented with a choice between "clean but sluggish" or "fast and dirty", performance will often win out over environmental concerns in crucial buying decisions. Thus, widespread environmental benefits will be realized only by developing a "clean and fast" machine, which appears difficult using a four-stroke cycle approach. For this reason, the CSU team chose to focus on developing a clean two-stroke cycle engine – the "fast and clean" solution.

After selection of a two-stroke approach, the team examined platform options. The final selection was a 3-cylinder 600cc Arctic Cat engine. The engine was sleeved to reduce the cylinder bore to meet the competition's 500cc displacement guideline. An oversize engine was selected since sleeving was required to help separate the scavenging/intake air from the engine's crankcase.

THE TWO-STROKE CYCLE APPROACH

The unfavorable emissions from conventional two-stroke cycle engines are primarily due to: 1) short-circuiting of fuel during scavenging, 2) incomplete scavenging, 3) the use of waste lubrication, and 4) poor control of air/fuel ratio. A review of these factors follows:

SHORT CIRCUITING

In a conventional crankcase-scavenged two-stroke engine, the combustion products from the previous cycle are forced from the cylinder with a new air/fuel charge. This charge is compressed in the crankcase by the underside of the piston and then enters the cylinder when the piston uncovers the transfer / intake port. Unfortunately, the exhaust port is open during the entire time that the intake port is open – allowing part of the air/fuel mixture to "short circuit" through the cylinder during the scavenging process. This is the major source of the high hydrocarbon emissions from crankcase-scavenged engines.

INCOMPLETE SCAVENGING

The maximum volume change in the crankcase of a crankcase-scavenged engine is equal to the swept volume of the engine. Due to pumping losses, the volume of air/fuel mixture used for scavenging is less than the swept volume of the cylinder (i.e., the delivery ratio is less than unity). There is not enough mixture to force the old exhaust products from the cylinder, resulting in high levels of residual exhaust which remain in the cylinder. This is a major contributor to combustion instability which in turn contributes to high carbon monoxide and hydrocarbon emissions. The efficiency of the scavenging process can be improved by increasing the scavenging volume, but this will increase the hydrocarbon emissions if the engine is scavenged with an air/fuel mixture.

WASTE LUBRICATION

Production two-stroke cycle snowmobile engines use a waste lubrication system. In this system, the oil is mixed with the air and fuel as it enters the crankcase. Some oil is deposited on the appropriate components (crank bearings, rod bearings, cylinder walls) while the mixture is in the crankcase. The oil then travels with the air/fuel mixture into the cylinder where it is either short-circuited or trapped in the cylinder. The short-circuited oil contributes to hydrocarbon emissions. The oil trapped in the cylinder does not burn readily and is a prime source of the visible smoke produced by snowmobiles.

AIR/FUEL CONTROL

All but a few snowmobiles are carbureted. Snowmobile carburetors are typically set up for rich operation; this optimizes power and provides "fuel cooling" of the cylinder to help prevent overheating of the piston. Leaner operation for emissions control is possible, but the setup procedure requires diagnostic equipment that is not commonly available to recreational snowmobilers. Even with access to the diagnostic equipment, a carburetor must be set up for a specific temperature and elevation. These conditions will often change during a day of snowmobiling, producing significant variations of the in-cylinder air/fuel ratio.

DESIGN OVERVIEW

In order to address the shortcomings inherent to conventional two-stroke cycle snowmobile engines, the CSU direct-injection engine represents a comprehensive redesign of the engine's scavenging, fuel delivery, lubrication and silencing systems. The engine design can be summarized as follows:

- Scavenging with air only through an external Lysholm twin-screw compressor
- Direct in-cylinder injection after exhaust port closure
- Lossless lubrication system
- High efficiency reactive / absorptive silencer
- Oxidation catalyst housed in the exhaust silencer

These elements are described in more detail in the following subsections.

EXTERNAL SCAVENGING SYSTEM

As discussed previously, the biggest contributor to high hydrocarbon emissions is short-circuiting. In order to reduce scavenging-induced hydrocarbons, we adopted an approach which utilizes air-scavenging with direct in-cylinder fuel injection.

Research at CSU's Engines & Energy Conversion Laboratory on large industrial 2-stroke cycle engines has shown significant benefits from "over-scavenging" – using delivery ratios greater than unity in order to improve the percentage of new air in the cylinder (charge purity). The delivery ratio, Λ, is nominally defined as:

$$\Lambda = \frac{\text{mass of delivered air per cycle}}{\text{mass of trapped cylinder charge}}$$

If "perfect displacement" scavenging were achieved, i.e. scavenging with no displacement or mixing, all of the exhaust products would be expelled from the cylinder with a scavenging ratio of unity. In practice, significant mixing and short-circuiting do occur, so overscavenging is useful to improve charge purity. As we have already discussed, overscavenging cannot be achieved with crankcase-scavenged engines since pumping losses reduce the volume of air swept into the crankcase to less than the swept volume of the engine.

In order to increase the scavenging efficiency on CSU's engine, an external scavenging pump was used to increase the scavenging ratio. An Opcon twin-screw ("Lysholm" type) blower/compressor was used for scavenging. The blower had a built-in pressure ratio of 1.3 and a swept volume of 323 cm^3/revolution. The blower was belt-driven off the crank with sheaves sized for a 2:1 speed increase, providing 646 cm^3 of air on each engine revolution – providing a delivery ratio of 1.3. The air from the blower is delivered to an air manifold which then delivers the air into the intake air plenum on each engine. The Opcon twin-screw blower and air manifold are shown in Figures 1 and 2.

The external scavenging system has a positive benefit on engine silencing. The use of forced scavenging reduces the reliance of engine scavenging on exhaust system dynamics, reducing the need for bulky tuned exhaust pipes. The scavenging system also allows the use of a more efficient (albeit restrictive) exhaust system. The twin-screw scavenging pump isolates hard-to-silence low-frequency noise from the engine intake. An intake silencer is still required to reduce the high frequency noise produced by the blower, but this is much easier to attenuate than the lower frequency blowback and induction noise which is emitted from a two-stroke engine's intake.

DIRECT IN-CYLINDER FUEL INJECTION

We evaluated several options for direct in-cylinder fuel injection, including high pressure and air-blast and injection systems. Ultimately, the Ficht™ impact-type fuel injection system was selected due to its simplicity; it it does not use compressed air, which is required for air-blast fuel-injection systems. It uses a low pressure fuel supply and then increases the pressure through the impact of a weighted pintle on a "piston" inside the injector. The system has been applied successfully to larger two-stroke engines used on outboard motors and personal watercraft, but has not yet been used in a production snowmobile application.

The Ficht™ technology has been licensed by Outboard Marine Corporation (OMC). OMC has granted licenses to use the Ficht™ technology for snowmobile applications to both Arctic Cat and Polaris. Due to commercial concerns by its snowmobile licensees, OMC was prevented from providing technical support for the CSU effort. Withdrawal of support occurred too late in the development process to utilize an alternative technology, so the team proceeded with the development effort using parts available on the open market. Fuel injection components were obtained from the smallest high-speed application of the Ficht™ technology - a 3-cylinder 1300cc Polaris personal watercraft.

New heads were fabricated to allow mounting of the Ficht™ / Polaris injectors on our 3-cylinder 500cc (600cc sleeved to 500cc) Arctic Cat engine. These heads were fabricated from aluminum using a CNC mill / machining center. The injector mounts were configured with an 8° offset angle which allows the injector to wet the spark plug electrode but not to wet the walls of the combustion chamber. The new heads were designed with a higher compression ratio, increasing the compression ratio from 6.4:1 to 7.1:1 (defined using the volume trapped above the exhaust ports). The internal volume of the new head design is shown in Figure 3. A finished head is shown in Figure 4. The assembled engine is shown in Figure 5.

The 1300cc injectors are grossly oversized for the 500cc engine used for the competition. Initially, the team planned to use a combination of mechanical modifications and recalibration of the engine's ECU to reduce the fuel flow to acceptable levels. Ultimately, recalibration was not possible without technical support from the manufacturer. The team examined the possibility of creating new driver circuitry and utilizing a programmable engine controller, but this proved to be prohibitive due to the accelerated development cycle of the competition. The team evaluated mechanical alterations to the injectors in which the pintle travel of the injectors were reduced. This reduced the fuel flow but produced erratic operation. The engine was developed to the point where it would start and operate, but the in-cylinder fuel/air mixture was too rich to be competitive in the competition.

LUBRICATION SYSTEM

The elimination of the waste oil lubrication system required several engine modifications. A new cylinder sleeve and redesigned piston skirt were designed to block off the transfer ports from the crankcase, preventing scavenging air from entering the crankcase, thereby eliminating mixing of the oil and intake air. The original intention was then to use splash lubrication and forced flow to provide lower end lubrication. Errors in fabrication by the piston and sleeve manufacturers prevented the isolation of the crankcase from the air manifold. This allowed scavenging air to enter the crankcase which in turn required abandonment of the lossless wet-sump lubrication concept which was originally selected.

Using the sleeves and piston as received, the intake air is not sealed from the crankcase, so a modified approach was adopted – using forced lubrication to the main bearings and mist lubrication for the rod bearings and piston walls. In order to ensure adequate lubrication of the piston walls, an "oil-wetting" boron/molybdenum coating was used to "bond" lubricating oil to the piston walls. The engine was not operated for long enough to yield a reliable quantitative assessment of the lubricating system, but visual examination of the cylinder walls show little wear after 15-20 hours of operation.

ENGINE SILENCING

The noise from a snowmobile is attributable to several sources. Exhaust noise creates a low frequency component at the firing frequency of the engine. The sharp pressure pulse as the exhaust ports open creates high frequency noise components. Intake noise is created by the backflow of exhaust gases through the intake ports and by the inrush of air into the cylinder. Finally, mechanical noise is emitted from reciprocating engine components and from the snowmobile track and drivetrain.

Traditional snowmobile exhaust systems incorporate large bulky tuned pipes which occupy much of the forward volume under the hood of the snowmobile. The use of a twin-screw compressor reduces the need for tuned pipes and opens up this space to house a high efficiency exhaust silencer / oxidation catalyst. The area previously taken up with the intake box used for snow dropout is used for an intake air filter and intake air silencer.

The use of a twin-screw compressor prevents the noise from intake-port opening from traveling through to the engine intake, effectively eliminating the low-frequency source of intake noise. Unfortunately, the twin-screw is an efficient producer of high frequency noise at the meshing frequency of the blower. Since the blower noise is primarily high frequency, an absorptive type silencer was designed to absorb the high frequency noise. An air filter upstream of the silencer is used to block snow and to remove moisture and dirt from the intake air stream.

An exhaust silencer was designed in which reaction elements are used to attenuate noise at the firing frequency and at its first harmonics. A large expansion chamber is tuned to one-quarter of the fundamental firing frequency of the engine to attenuate the lowest frequency noise. A smaller reaction chamber and a tunable side chamber are used to attenuate mid-range components. An absorptive exhaust diffuser is used to remove high frequency components as the exhaust gas exits the engine. This exhaust silencer is more restrictive than those used in the helmholtz-tuned expansion chambers usually used on two-stroke cycle engines. With the use of forced scavenging, however, this slight restriction does not degrade scavenging so little reduction in engine performance is expected.

The silencing system was never fully implemented. The intake silencer and absorptive exhaust diffusers were never built and the exhaust silencer used for testing used only a single reactive element. Quantitative testing of the complete silencer is anticipated during the follow-on project.

CATALYTIC CONVERTER

The energetics of hydrocarbon loss during scavenging provide a formidable challenge to the use of oxidation catalysts on conventional two-stroke cycle engines. The energy content of unburned hydrocarbons and carbon monoxide can be as high as several kilowatts in a conventional crankcase-scavenged two-stroke engine. If all of this chemical energy is released on the surface of the catalyst, catalyst damage will occur quickly. In addition to the problem of catalyst overheating, oil which is carried through into the exhaust can “poison” the catalyst with sulfur and mask the catalyst with ash.

The use of a direct-injection engine reduces hydrocarbon and carbon monoxide levels to the point where a high-efficiency oxidation catalyst can be used without meltdown. A lossless oil system greatly reduces the danger of catalyst poisoning.

Two oxidation catalysts were built to CSU specifications by Miratech Corporation of Tulsa, Oklahoma. These catalysts uses a platinum / palladium washcoat over a corrugated stainless steel substrate. The catalysts are configured in series and housed in the main reaction chamber of the exhaust silencer. Housing the catalysts in the silencer is primarily a matter of convenience, but is also expected to remove some high frequency noise components from the exhaust stream. The two oxidation catalyst elements are shown in Figure 6. An cross-section of the exhaust silencer housing the oxidation catalysts is shown in Figure 7.

As discussed previously, the engine’s fuel map was not properly calibrated so the trapped air/fuel ratio was extremely rich. In order to prevent damage to the catalyst, the team decided not to install the catalyst until the engine could be operated lean of stoichiometry.

IMPLEMENTATION

The design of CSU’s externally-scavenged, direct-injection engine was a very ambitious undertaking, particularly given the 9-month development window. Several setbacks occurred during the development. New pistons and sleeves were designed in order to close off the transfer ports. Unfortunately, manufacturing errors by the suppliers meant that the transfer ports could not be closed off. There was insufficient lead time for new parts to be produced so the lossless lubrication system designed by the team could not be used. This required a change to a waste lubrication system which was one reason that the catalyst system we designed was not tested.

The second major deviation from the intended design was discussed under the “Fuel Injection” section. An offer by the manufacturer to provide technical support for calibration was withdrawn due to commercial concerns by the manufacturer’s licensees. This prevented final calibration of the ECU. The condensed development cycle meant that there was insufficient time to pursue alternative strategies including development of the injector driver circuitry which would allow the use of a commercially available development ECU (MOTEC or other). This was a serious setback and ultimately prevented the use of the engine in the competition.

Although operational, the state of engine development was not mature enough for competition, so a less ambitious carbureted engine was used in the CSC 2000 competition.

EXPECTED RESULTS

Due to increased scavenging efficiency and the exclusive use of air for scavenging, the engine is expected to produce similar or greater levels of engine power without resorting to rich operation. Elimination of rich operation is expected to reduce engine-out emissions of carbon monoxide. The use of air alone for scavenging is expected to reduce engine-out emissions of unburned hydrocarbons. The use of an oxidation catalyst will further reduce CO and THC emissions. Our projections of engine emissions indicate that levels of hydrocarbons and carbon monoxide should be below 10 gm/bhp•hr, which represents a 98%-99% reduction in emissions of both components.

The use of a high efficiency reactive / absorptive exhaust silencer is expected to reduce noise levels well below the 74 dBA noise requirement established by the competition.

CONCLUSION

A two-stroke cycle engine was designed using external scavenging and direct in-cylinder fuel injection. In addition to providing efficient scavenging, the use of the external scavenging system allowed the use of a high-efficiency reactive silencer, which was also used to house an oxidation catalyst.

The direct-injected engine was not sufficiently developed for use in the Clean Snowmobile 2000 competition. Further development of this concept will be carried out by a student team who will participate in the Clean Snowmobile 2001 Competition.

CONTACT

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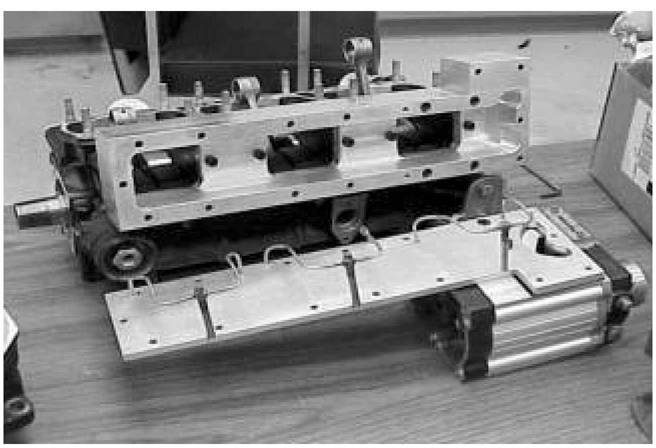

Figure 1 – Air manifold showing oil injector nozzles

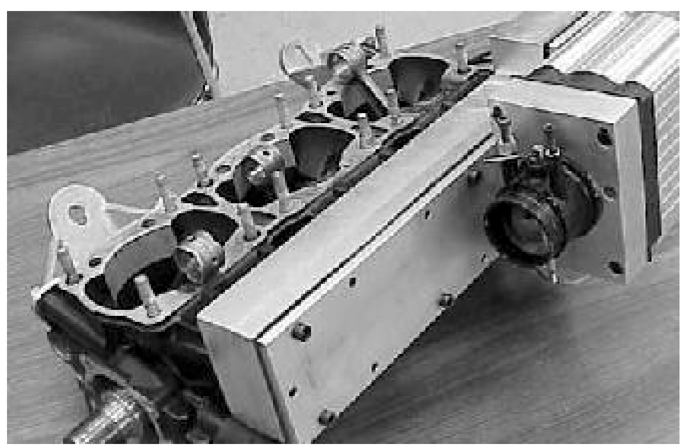

Figure 2 – Air manifold, throttle body, and twin-screw scavenging blower

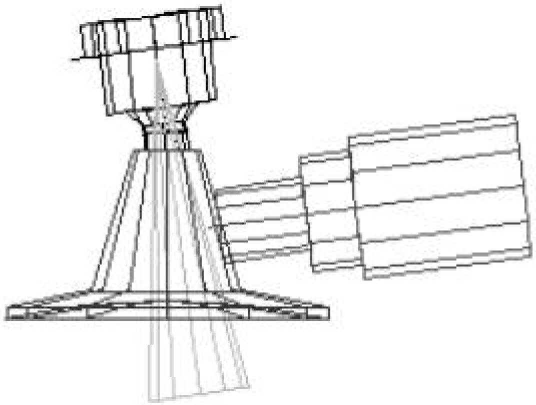

Figure 3 – Internal volume of head showing injector spray pattern of angled injector

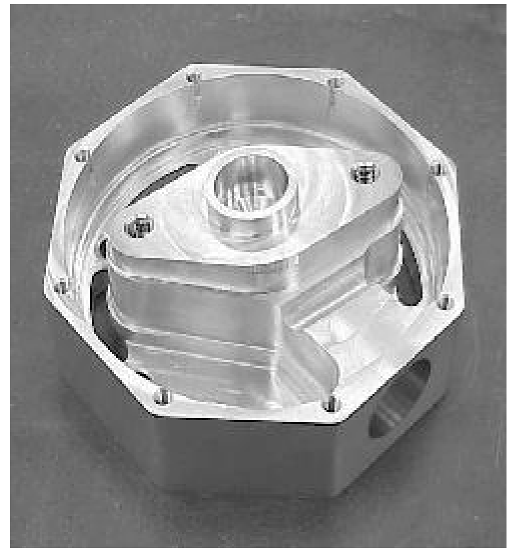

Figure 4 – CNC-machined head without top cover

Figure 5 – Assembled engine showing mounting of Ficht™ Fuel Injectors

Figure 6 – Oxidation catalyst elements for inclusion in exhaust silencer

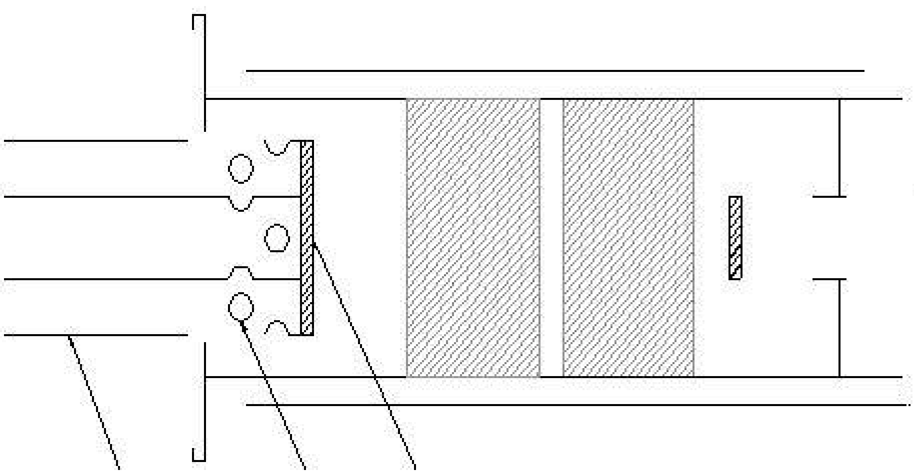

Figure 7 – Primary reaction chamber of exhaust silencer showing mounting of oxidation catalysts